6

Knowing what is out there

So far we have mostly considered the species richness that is already known to exist, and the mechanisms which may control this. However, it is clear that not all the world's species have so far been discovered. Every year, biologists find thousands of "new" species (i.e., new to science), and describe and name them. Most of the new species that are presently being discovered are either insects, or their relatives the mites that are universally present in forests and soils, or the little nematode worms that burrow into sediment everywhere. Additionally, some of each year's new species are plants and a few of them are birds, mammals, or fishes.

Given that we do not yet know every species out there, there are some questions which have to be asked. For instance, how much uncertainty is there about species richness patterns? How can we estimate the number of species that are still awaiting discovery? And how were the existing totals for global biological diversity arrived at? Are they reliable in the first place?

6.1 NATURE'S CURRENT TOTALS

Centuries of hard work by thousands of biologists have led to somewhere over a million living species being formally described, named, and listed. This is the business of taxonomy, of finding and describing the diversity of life. Most members of the general public (and most ecologists, too) assume that there must be some central database of all the species so far described in the world, so that it will be possible to obtain an unambiguous figure on the known number of species in every group of organisms. The real situation is far more chaotic.

A few brave souls have attempted to pull together information, to come up with more precise totals for the numbers of species found in each of the broad groups of life. Although the estimates in these different studies are mostly of the same order of magnitude, they do vary quite a lot. For example, one estimate published in 1990 has

it that there are 45,000 known species of mollusks, and another published the same year says there are 100,000 of them (Groombridge, 1993). This says something about the difficulties that are inherent in the business of species counting.

What is evident from published figures, and Tables 6.1 and 6.2, is that the estimates for the most diverse groups are rounded, because they tend to be given as even thousands. That is the best anyone is able to do for the time being. There are just too many species in these groups for it to be worth the effort of counting every last one that has ever been recorded by science (especially as the number always changes from one year to the next).

Something that makes the task harder is that for most groups of organisms, there is no central list where each new species is added as it is discovered. The raw information on the discovery of new species remains dispersed through hundreds of specialized scientific journals. For example, in the case of insects there are several learned societies and institutions around the world that provide lists and guidebooks (known as floras and faunas), and new descriptions of species in their journals. One example is the American Entomological Society, which publishes *Entomological News*, published several times a year and packed full of new insect species descriptions. It is the same for plants, for mollusks, and so on. Because the information is so voluminous and so scattered, anyone trying to compile an overall total for global species richness must in effect fit together a lot of jigsaw pieces from different sources. When Brian Groombridge, Martin Jenkins, and their colleagues (Groombridge, 1993; Groombridge and Jenkins, 2002) came up with their totals for the world's current known biological diversity (Tables 6.1 and 6.2) it was partly a result of phoning around or writing to a lot of experts in different fields of taxonomy who could put a plausible number down. Each of these experts must in turn have relied upon combinations of other, smaller jigsaw pieces of information. These were the estimates of total known species within particular narrow subgroups, obtained from the specialists who work on them.

Adding to the problems involved in reaching an overall total is the fact that not all species discovered and named in the scientific literature survive scrutiny. Months or years after a species has been named, other taxonomists may take a closer look at it and decide that this species is really just the same as one that had already been described by someone else. The problem of "double description" was especially bad in the recent past when taxonomists were working independently because they were separated by linguistic and political barriers (e.g., the Soviet or Chinese taxonomic literature vs. Western taxonomic literature) and the mess is still being sorted out.

Even with good communications, the problems of double description are huge. Among insects, for example, somewhere between one-fourth and one-third of the new species described each year turn out to be ones already named by others—so they are removed from the lists (Groombridge, 1993; Groombridge and Jenkins, 2002). It is difficult to keep pace with such turnover in names, and any list made up of the new species just announced within the scientific literature will contain many which eventually turn out not to be accepted by the taxonomic community, so they in effect vanish. The best estimates of the world's known species try to take this attrition rate

Table 6.1. Current totals of known species for certain prominent groups of organisms.

Colloquial name of group	*No. of species in group*
Vertebrates	
Mammals	4,630
Birds	9,750
Reptiles	8,002
Amphibians	4,950
Fishes	25,000
Invertebrates	
Insects	950,000
Mollusks	70,000
Crustaceans	400,000
Others	—
Plants	
Gymnosperms (Coniferophyta, Cycadophyta, Ginkgophyta	876
Angiosperms (Anthophyta, flowering plants)	250,000

Source: Groombridge and Jenkins (2002).

Table 6.2. Current known species for major groups of life, left-hand column. Some plausible estimates for the total number of species "out there" (including those as yet undiscovered) are in the right-hand column.

Domain	*Eukaryote kingdoms*	*No. of described species*	*Estimated total*
Archaea		175	?
Bacteria		10,000	?
Eukarya			
	Animalia		1,320,000
	Craniata (vertebrates), total	52,500	55,000
	Mammals	4,630	
	Birds	9,750	
	Reptiles	8,002	
	Amphibians	4,950	
	Fishes	25,000	
	Mandibulata (insects and myriapods)	963,000	8,000,000
	Chelicerata (arachnids, etc.)	75,000	750,000
	Mollusca	70,000	200,000
	Crustacea	40,000	150,000
	Nematoda	25,000	400,000
	Fungi	72,000	1,500,000
	Plantae	270,000	320,000
	Protoctista	80,000	600,000
Total		*1,750,000*	*14,000,000*

Source: Groombridge and Jenkins (2002).

into account, lowering the total by a certain correction factor to allow for the ones that will eventually be removed.

So, accepting all the limitations in any estimate, what is the overall picture so far for global species richness? The compilation put together in 2002 by Martin Jenkins and Brian Groombridge of the World Conservation Monitoring Center (Table 6.1) seems likely to be as good as any.

All in all, something like 1.75 million species have been identified so far. One thing that leaps out of the totals in Table 6.1 is how many types of insects there are: somewhere around 800,000 to 950,000 species of them have been found so far (Groombridge, 1993; Groombridge and Jenkins, 2002). The next most diverse group is the flowering plants—the angiosperms—with more than 250,000 species. Although vertebrates such as mammals, reptiles, and fish tend to get a lot of attention, far fewer species of these backboned animals have been discovered so far—several tens of thousands. The majority of known vertebrates are fishes (around 25,000 species), and next most diverse are the birds (around 10,000 species). For mammals we know of around 4,000 species, the majority of these being rodents (mice, squirrels, and suchlike) and bats. There is a similar number of known amphibian species, most of these being frogs.

6.2 IDENTIFYING NEW LIFE FORMS—TAXONOMY AND ITS CHALLENGES

We have seen the overall totals of known species, but how exactly do the raw data come about? How is a new species found and identified, and officially announced to the world? This business of discovery and description has its own craft, its own long traditions and even its own language (Taxonomic Latin). The name of this craft is taxonomy—and the guilds which its craftsmen and women belong to are the taxonomic unions.

In a sense we are all taxonomists. Humans have probably always wanted to enumerate and classify the organisms around them—there is basic survival value in knowing what is useful and what is harmful out in nature, and this needs some sort of classification, identification, and naming (even if it is very rough and ready, and unwritten). Written accounts of the diversity of life go back as far as the ancient Chinese and Greeks, and there are others from the time of the ancient Romans. In the 1600s, a shaking up of European academia by the Enlightenment led to a fresh burst of interest in nature, and that included going out into the world and classifying whatever could be found. For instance, the English botanist John Ray and his students traveled extensively in Europe, and collected, described, and named many hundreds of plant species in a series of books. However, the detailed traditions of modern-day taxonomy have their origins more with a later generation of natural historians who worked in the 1700s. This began when the process was formalized and greatly advanced by a Swedish biologist who is nowadays known by the Latinized version of his name—Carolus Linneaus.

Linneaus came up with a simple way of naming each species, using two Latin names. In Linneaus' system, the first name is used for the cluster of closely related species that it belonged to, known as the genus. The second name is reserved only for that unique species. So, for example, the North American white oak tree I see outside my window as I write is known formally in biology as *Quercus alba*. The first name—*Quercus*—means "oak" in Latin, and is the genus or generic name used for all oaks. The second name *alba* means "white" in Latin, and is the specific name—reserved for that species in the oak genus. Generic and specific names are many and varied. Some are straightforwardly descriptive, such as the name *Quercus alba*, but others are named after the colleagues, friends, or family of the taxonomist who discovered or first described the species or genus. So, for example, the flowering plant genus *Stewartia* was named by Linneaus in honor of a friend of his who was a respected Scottish botanist.

Before Linneaus, only long meandering Latin names involving 10 or 20 words had been used to describe species—without any short snappy name to use. Linneaus' two-name (or binomial) system proved to be a good practical way to label a species; not too long, but with the genus name putting each species in the context of other things it resembled. Linneaus also went further, suggesting a hierarchy of categories that further placed each species into the wider framework of life. In the opinion of my eclectic and ever-curious former tutor at Oxford, Barry Juniper, the system that Linneaus came up with was based loosely on the way librarians in medieval Europe categorized the books within their collections: they too used a "binomial" system to classify them—first a word for the general category, and then a word that specifically described that particular book.

Linneaus was a fanatical worker, and he named and classified thousands of species in his lifetime. His students voyaged around the world aboard trading vessels in search of new forms of life to bring back to him, often losing their own life in the process. The tradition that Linneaus started and passed on to others continues today, with various modifications to his techniques

It is interesting that Linneaus himself had earlier in his life been made to adopt a Latin binomial to describe himself. In Sweden in those days, people traditionally did not have a surname as such. But to enroll in a university, each student had to adopt a single snappy surname that administrators could handle, and Linneaus chose a Latinized version of a name that described the farm he came from. The word *Linneaus* means "a big linden tree", something which grew close to the family farmhouse.

6.3 THE STAGES IN DISCOVERY OF A NEW SPECIES

The story of the discovery of each species is unique, but there are certain common patterns to these stories. In general, nowadays the discovery and naming of a new species goes through several different stages.

6.3.1 Collection

First, a specimen of a previously unknown species is collected by biologists on fieldwork or by interested amateurs. It may already have been noticed as something unusual and unknown at the time it was collected. Often, instead of having immediately been recognized as new, it will just have been collected incidentally by ecologists, as part of a general inventory being made to try to summarize the species composition of a particular place. For example, it might be just another plant in a bag full of specimens taken back for identification, or just another insect or mite among many in a bottle of preserving alcohol.

Sometimes, taxonomists themselves go out collecting in the hope of finding new species—although nowadays there does not tend to be very much money available for such fieldwork. More often they must rely on material that was collected as a part of other studies, or collected specially for them on request by friends who are ecologists or conservationists.

There are many different stories of how new species were discovered serendipitously. Some species have first been recognized as new by chance after they sat in museum collections under another name for decades or even centuries. One recently discovered mammal known as the rat-squirrel (*Laonastes aenigmamus*) was first identified from a killed specimen on sale for food in a village market in Laos (see below). There is one tale (possibly just apocryphal) that an insect taxonomist collected a new species of beetle when it fell into his gin and tonic as he sat outdoors at a bar. He is said to have given it the very apt name of *ginandtonicus*. I tried to verify this story, but I can find no reference to a species of this name in the academic literature—so it looks to be a sort of taxonomists' urban legend.

6.3.2 Identification

Let's suppose that a taxonomist or an ecologist collects a range of material out in the rainforest: for example, the shoots of plants that are put in bags, or insects trapped in a net then kept preserved in alcohol. The next stage is to get the collected specimens to somewhere where they can be identified. Most often, ecologists will try identifying the material they collect themselves back at the field station or lab, using "keys". These keys are books (or computer software) which guide biologists through the identification process until they eventually arrive at the name of the species that they are looking at. When the collectors cannot successfully "key out" a specimen to something that is in the books, it is possible that this is a new species, previously unknown to science. The specimens may then be sent to a specialist in that particular group of organisms, whether it be beetles, birds, bivalves, or whatever. Such experts tend to be employed at museums and zoos or botanical gardens, or sometimes in university departments. Taxonomists who are prepared to take on the task of trying to describe and identify new species are known in the trade as "alpha taxonomists" (somehow this term makes me think of "alpha male" silverback gorillas, though I am not sure if that is how alpha taxonomists think of themselves).

So looking carefully at a specimen, and comparing it with published descriptions of other species—or actual specimens preserved held in the collections—the expert can decide whether it is a new species or not. Increasingly nowadays, techniques that focus on DNA are also used to help figure out whether a specimen belongs to a previously known species, and if so what species it is. A small part of the organism, such as the leg of an insect or a leaf, is sent to the lab and analyzed to produce a "DNA barcode". This is a profile of genetic information which can be compared against other known species. If the DNA barcode looks very different from anything already known, the specimen is worth a second look by a taxonomist.

Another new technique currently under development is to use an "automated recognition system": a computer program that has been taught to recognize specimens of a range of species from color patterns and shapes. A digital image of the specimen is examined by the program—and if it is in the database it is identified. If it is not in the database, it could be a new species. This may turn out to be the way of the future, but at present the development of this technique is in its very earliest stages, and not reliable enough to use for anything other than cursory identifications that help narrow down what group the specimen belongs to.

In the end, the decision whether to name something as a new species, or just as a slightly different variety of an existing species, is often rather subjective. We do not usually have any sure way to know that the new species doesn't intergrade with some other described "species" somewhere out there in nature. Or perhaps it would hybridize easily with some other species it doesn't normally encounter, it if was given the chance. In either case both "species" should probably just be relegated to "subspecies", if we actually knew enough about them.

Taxonomists who are reluctant to name new forms of organisms they find as separate species are called "lumpers": they lump things together into the same species. Those who tend to label each variety they find as a new species are called "splitters": they tend to work by splitting up the world into a greater range of species. The overall species richness we find in the world depends upon the balance between the activities of these splitters and lumpers, and how many species they each feel like describing. Across the broad field of taxonomy, there are local traditions that tend more towards splitting or lumping—often partly depending on the influence of one particularly prominent taxonomist and his or her former students. Scores of species can sometimes vanish overnight when someone takes a new look at the classification of a group and decides that the "species" in it are not really separate species at all, but just local varieties. At other times swarms of species can suddenly appear after a taxonomist attempts a revision of another's work and finds reason to split varieties or subspecies into fully-fledged species. This is what ecologists such as myself must contend with in the study of species richness—we deal with the raw material that taxonomists choose to hand us, and which they sometimes take away again later.

6.3.3 Description and naming

So a new species has been discovered. What happens next? It is necessary to announce the discovery of this species to the world, just as the birth of a baby is announced by

sending out cards. The taxonomist writes a careful description of a specimen (known as the "type specimen"), typically consisting of several pages written in English with Latin-based technical terms that precisely convey what it looks like—and what makes it differ from all other species known. Usually a precise drawing of the specimen is also provided, produced by a specialized zoological or botanical artist. This description is published in a scientific journal (e.g., *Entomological News*, which I mentioned above), often the in-house journal of a zoo or botanic garden (e.g., the *Kew Bulletin*, in the U.K.) which may publish hundreds of new species descriptions each year.

It used to be possible to name a new species after just about anyone or anything. Taxonomists would name a new species after themselves, their latest sweetheart, or their children ... or (perhaps) give it a funny name like "*ginandtonicus*". Then the taxonomic unions decided this was getting too much and clamped down. Nowadays it is not possible to name a species after oneself, nor just any old friend or family member: only serious scientists, or just occasionally famous media people.[1] Any names like "*ginandtonicus*" are definitely out.

When the description of a new species has been made, the original specimen is carefully preserved, as a reference point for any future taxonomist who wants to come back and check on the identification. If it is an insect, it will probably be pinned out in a specimen drawer next to rows of other insects. If it is a plant, it will be pressed and dried between sheets of paper and filed away rather like a book. And if it is a mammal, it will probably be preserved floating in a bottle of formalin. This preserved individual is known as the "type specimen". There is only one fully described living species, however, for which no type specimen has been preserved, and that is humans. When producing his first work classifying animal life, Linneaus described himself for the published description of humans. However, he did not leave his body to science to be preserved!

6.4 THE UNCERTAINTIES IN CURRENT ESTIMATES OF SPECIES RICHNESS

Everyone working in the field of biological diversity agrees that there must be many unknown species still out there, remaining to be discovered by science. The ease with which new species can be discovered in certain parts of the world makes it clear that there are a lot more to find. I am told that a single day's fieldwork, collecting thousands of insect specimens in a remote area of tropical rainforest, is sure to yield several new species of insects. A day spent collecting hundreds of plant specimens in a previously unsampled locality is also quite likely to yield a new species of rainforest plant. A single deep-ocean trawl from a research ship is likely to yield new species of invertebrates from the sea bed. It just makes sense then that there must be a lot more species out there, still undiscovered.

[1] The American comedian Richard Colbert recently had a newly discovered species of spider from California named after him, after his alter-ego character on *The Colbert Report* stated that someone ought to name a spider in his honor.

However, it is not quite as easy to discover new species of certain other forms of life. For example, new mammals and birds are relatively difficult to come across. At the time of writing in 2008, typically a dozen or so new species of mammal are found each year—most of them rodents, the most diverse group of mammals in the world. This figure is down from around 37 new species a year in the 1970s and 1980s (Groombridge, 1993), suggesting that the supply of undiscovered mammal species is running out. Around half a dozen species of birds are discovered in the world each year, suggesting that there are fewer birds than mammals still left to be found.

Various biologists have tried to put a figure on how many species still exist undiscovered in nature, something I will talk about later. It seems strange, actually, that we could ever try to quantify things which we have not yet found. Yet this is just an extension of the same commonsense principle that if we can find several new species in a single day's collecting in the rainforest, there must surely be a lot more species there in the forest.

If we just had a limited geographical perspective and only considered the showiest groups of animals and plants, it would be easy to get it completely wrong about how many species there must be in the world, including the undiscovered ones. Taxonomists tend to be specialized in one particular group of animals and plants, which must bias their own perspective, and they are also limited by the state of knowledge of the time that they are living in. For example, in the late 1600s the pioneering taxonomist John Ray suggested that there must be about 10,000 to 20,000 species of insects in the world. Even just in Europe, there are actually a lot more types of insects than that! Ray's perspective on the world's diversity would have been biased by most of the work having been done on larger, showier insects and then mostly in Europe, without much knowledge of all the small drab ones and also the vast diversity of some other parts of the world. In fact, we now already know of about 900,000 insect species—and still counting.

Despite the difficulties of coming up with a reliable estimate, biologists are still fascinated by the question of how much is really out there in nature. Using some mathematics, plus a more careful global perspective based on the much greater amount of collecting that has been done these past three centuries, we can just maybe pin down the numbers a bit better. One way to try to make an estimate of how many undiscovered species are still out there is to plot a graph, showing how many known species have accumulated over time. Because of the different histories of study of different groups, each main group of organisms (e.g., fishes, beetles, mammals, etc.) shows its own individual curve, in terms of the cumulative total of species found (Figure 6.1). Some groups were very thoroughly sampled and studied even a hundred and fifty years ago. For example, half of the 10,000 bird species we now know of in the world had already been discovered by 1843—and most of the present-day total was known by the early 1900s. This general pattern of discovery is typical of organisms that are visually appealing, large, and easy to spot. The same goes for trees (large and imposing), butterflies (pretty and slow-moving), and mammals (generally furry and appealing, fairly large, and often relatively easy to spot).

Using a simple method, it is possible to make a rough estimate of how many species there are still out there remaining undiscovered. By following the slope of each

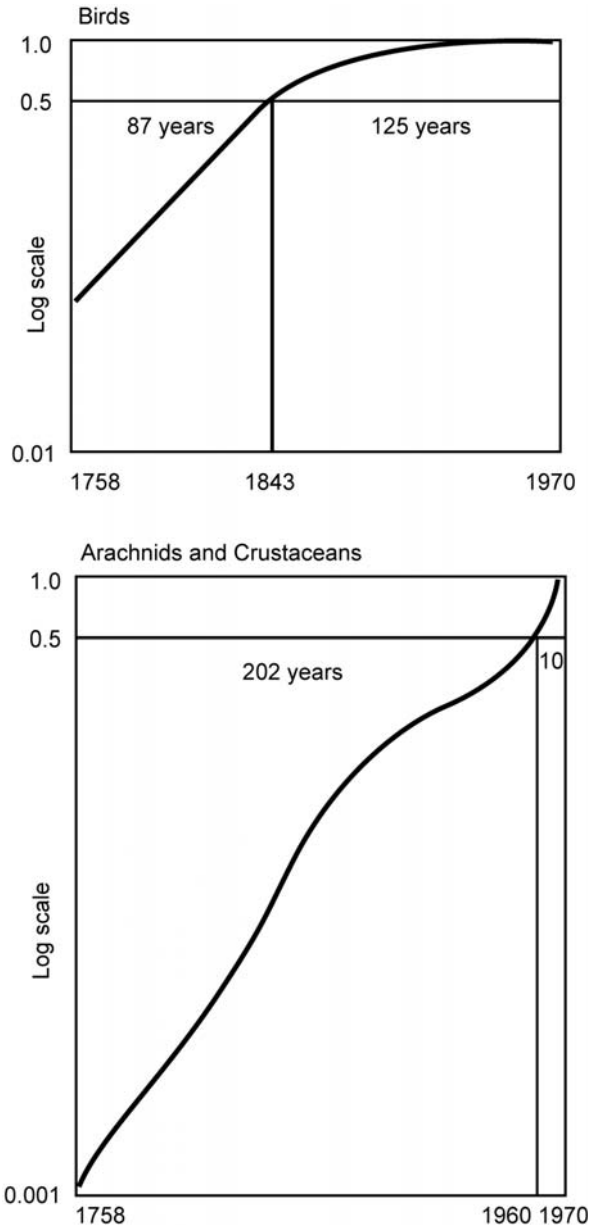

Figure 6.1. Cumulative known species reached by 1970 since the 1700s for two broad groups of organisms (top) birds and (bottom) arachnids and crustaceans, which include most of the known non-insect arthropods. Note the logarithmic scale. In birds, half the species were known by 1843 and the trend is leveling off. In the arachnids and crustaceans, the half-way mark was only reached in 1960, with a very steep rise in new species discoveries since then (after Groombridge, 1993, after May, 1990).

graph showing the number of known species for each group of organisms, and then continuing it onwards and upwards (a process known as "extrapolation"). If new discoveries of species in that group have started to level off, this probably means that we are already approaching the true total number of species out there: there is not much left to find then. The tell-tale sign is a slight bend in the line of the graph, called

the "inflection point". Once we have seen the inflection point, it may be possible to extrapolate the graph to the point where it would most likely reach a plateau, once just about all the species have been discovered. This can be done for particular groups of organisms, or in theory if we averaged enough different graphs it could be done for all the species on Earth. But because there is no central global database of species and because each group has own its individual trend, we cannot reliably plot one huge curve for all species on Earth. The best we can do is to look at groups individually, and try to make some reasonable guesses for each one about where the overall "true" species richness might be.

What this graph-plotting technique suggests is that for many groups, such as mammals, birds, fishes, and reptiles, we are close to knowing all of the species out there. This is even with all the best efforts of DNA technology and suchlike in finding new "cryptic" species (see below). With birds, for example, the main phase of discovery of species by science was in the late 1700s and 1800s as European naturalists first voyaged around the world. The cumulative curve of bird species found has now flattened off almost completely. For some other groups such as insects, new species are still being found as fast as ever, suggesting that we are nowhere near to finding all of them. One can also draw curves of accumulation of new species at a narrower taxonomic scale (e.g., in particular families). In the crow family Corvidae (Figure 6.2), the curve for the accumulation of known species leveled off many decades ago, suggesting that we are not likely to find any new members of this family.

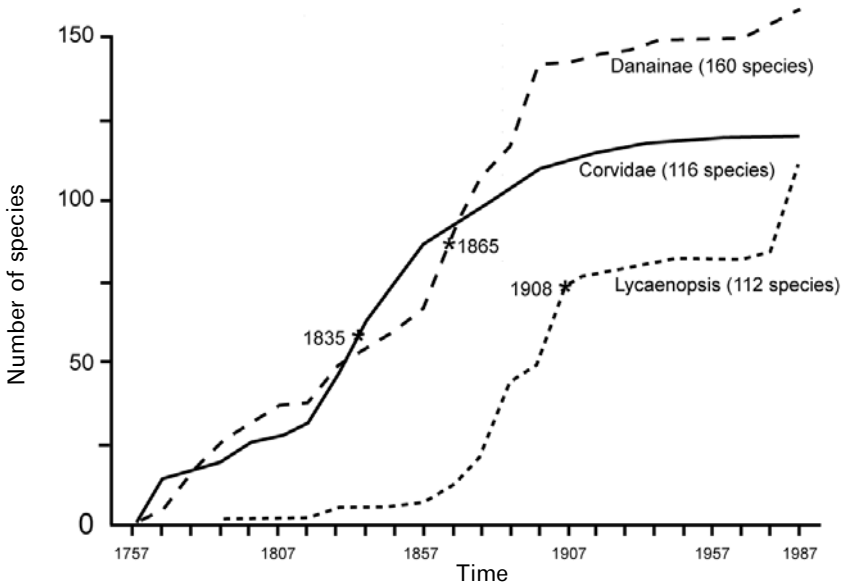

Figure 6.2. Cumulative known species since the 1700s in three taxonomic families of animals: the crow family (corvids), and the butterfly danids and lycaenids (after Groombridge, 1993). The corvids and danids leveled off early on, so apparently most species are now known. Lycaenids suddenly jumped up in richness in the 1960s as many more species were found in Asia.

However, even if the rate of discovery of species in a group of organisms has leveled off, there is still always a chance that it could undergo a renewed burst. The known diversity of the butterfly family Lycaenidae (the "blues") plateaued through the 20th century, but suddenly many more species were discovered after 1967 due to more extensive collecting in the mountains and islands of Southeast Asia, an area that happens to be especially rich in lycaenids. As a result there are now 33% more species of lycaenid butterflies that are known compared with 1967 (Figure 6.2).

Another approach to judging how many more species might be out there undiscovered is to do a much more localized study, with just a few samples of (say) insects in rainforest trees, or the invertebrates found in a series of trawls of the deep-sea bed. In these samples all the species are carefully identified, and the numbers of new species (new to that sample, though not necessarily new to science) in those samples are counted up. The rate at which new species are added with each extra sample is then extrapolated, to the total number of species—both named and unamed—in that general environment all across the world.

6.5 THE DEEP OCEANS: A BIG UNKNOWN

Deep oceans more than 3,000 meters deep cover slightly more than half of the Earth's surface. They are the main environment on Earth, yet they are a big unknown in terms of species richness. Visiting the deep-sea floor requires expensive technology, and back-up ships. For this reason, just a relative handful of biologists have ever seen this world directly and taken samples while they were down there. The only alternative is to trail scoops on long ropes from a research ship and then see what they bring up—a fairly haphazard way of sampling this vastness. Nevertheless, for the relatively few samples we do have, there are tantalizing signs of great biological diversity down there in the deep oceans. When Grassle (1989) tried trawling a scoop known as an epibenthic sled along the sea floor, he found that around half the species in each successive sample of sediment were new to science! These included crustaceans such as amphipods (shrimps and suchlike), and large numbers of different types of polychaete worms, as well as many tiny animals such as nematode worms. Grassle and Maciolek (1992) found that in their studies of the sea bed in deep water (1,500–2,500 meters down) off the east coast of the U.S.A., as a successively larger area of sea floor was sampled the rate of discovery of new species showed no sign of leveling off—again an indicator of a lot more out there waiting to be found. In their study they found a total of 798 species in just 21 square meters of sea floor (both known and new)—many only represented by a single individual. From the ease with which new species could be found on the deep-sea floor, Grassle and Maciolek suggested that there are at least 1 million deep-sea species, and perhaps more than 10 million. If they do exist, most of these species are still unknown to science. However, Robert May of Oxford University has poured some doubt on the idea that deep-sea diversity is really this high, pointing out that from the fact that half the species in these samples were already known, this should scale up to "only" 500,000 deep-sea species globally (still a very large number, and most of these still unknown). A later

study by Poore and Wilson (1993) that sampled at greater depths in the South Pacific suggested that diversity is higher there than in the sea off the eastern U.S.A. If this greater diversity in the Pacific is more representative of the oceans in general, then overall diversity of the oceans may be a lot higher than May suggested—perhaps pushing the figure back up into the millions for all the world's deep oceans. But for all we know, future estimates elsewhere on the ocean floors might counterbalance this with lower levels of species richness.

Estimates of the global diversity of deep oceans depend very much on certain other assumptions too. One is the assumption of how uniform they are in terms of species composition. It might turn out that many species are in fact very widespread if we sample broadly across a region of ocean floor. In a sense there is only one "climate" on the world's deep ocean floors: chilly (around 2–4°C) and dark all year round. This might mean then that the same sets of species can occur just about everywhere in the world, and so perhaps when one has thoroughly sampled just a few areas of the ocean floor, then most of what is out there has already been found? On the other hand, some newer studies have suggested that there is actually a lot of variation in species composition from one place to another in the deep oceans (e.g., between different ocean basins, and different depths within those basins, and even between different deep-canyon systems). It also seems that species composition and diversity in the deep ocean varies with latitude, in response to differences in the seasonal "pulse" of food from above (Chapter 2). It is difficult to try to average out all these different factors to get any reliable overall estimates of the world's deep-ocean diversity.

Given how much of the world is actually deep ocean, it is frustrating that we know so little about its biological diversity. There are just a few cursory samples, from which it is hard to scale up to the whole world.

6.6 OTHER TRICKS FOR ESTIMATING UNKNOWN SPECIES RICHNESS

A range of other tricks have been used to estimate species richness in particular groups, and some of these tricks are quite ingenious. However, ingenuity is not necessarily any assurance that a study in correct, because each set of sweeping predictions of global species richness rests on certain assumptions, which might or might not be justified.

One example was a clever attempt to estimate global species richness of fungi, based on looking at just one part of the world which is relatively well studied (Hawksworth, 1991). Hawksworth started by noting that 12,000 fungal species have been found in the U.K. If we compare this number with the total number of vascular plant species in the U.K., there are about 6 fungal species for each plant species (even though not all of them live off plants). Hawksworth then proposed an assumption: how about we assume that this ratio between plant and fungal species richness remains the same everywhere in the world? Since about 250,000 plant species have been found in the world, we need to multiply this by 6 to get the total number of

fungal species. This gives a huge global total of 1.5 million species of fungi, almost all of them still undiscovered.

While it is an interesting starting point for discussion, there are many possible weak links in this estimate. For instance, how do we know that the ratio of plant to fungal species is necessarily the same everywhere? Many of the 12,000 species of fungi in the U.K. do not attack living plants and rot down dead leaves and roots in soil, or attack living or dead animals. Thus it is possible that their diversity could depend on factors that do not so strongly parallel plant species richness, so their global diversity trend might not go in the same direction as plant diversity. Furthermore, particular plant species may occur over smaller areas than fungal species—many fungi appear to be extremely widespread, across thousands of miles or even globally. So whereas we may find a totally different set of plants if we move to another part of the world, many of the fungi could be the same—not adding much to their species richness. However, there seems to be a general feeling that the global species richness total for fungi is far greater than the current total of 70,000 species. Tropical fungi in particular are very poorly studied, and it does seem very plausible that in the damp, warm, and generally species-rich rainforests there could be many hundreds of thousands of fungal species out there—many of them adapted to attacking particular species of plants or insects.

6.7 A BOUNTY OF NEMATODES?

Nematodes are little, unglamorous worms that belong to their own phylum (Nematoda), quite distinct from the many other worm-like life forms in the world. They are anatomically fairly simple, with no legs or feelers, and many of them are very small—no more than a few millimeters.

Yet they are everywhere, in soils, in sea floor sediment, in the guts of animals, on the roots of plants ... So far no more than 15,000 species of nematodes have been found, but it is likely that there are still many more out there undiscovered. When taxonomists go over a sample of good nematode habitat with real determination, they find high species richness and many new species. For example, in one study a few cubic centimeters of coastal mud yielded 200 species (Groombridge, 1993). It is difficult to know how this diversity scales up if one samples more widely. Would we find more or less the same set of species in coastal muds everywhere, or a different set of species on every coastline? It seems quite reasonable to suggest that there might be at least several hundred thousand species out there (Groombridge, 1993), but this is still only a guess.

6.8 A PLETHORA OF MITES?

Mites are also low down on the scale of charisma. Most of them are little more than a speck to the naked eye, and many are too small to be seen at all without the aid of a microscope. They live in abundance in soil and leaf litter, playing a role as decom-

posers in food chains, but many others suck the juices of plants or live as parasites burrowing into the skins of animals.

Some 30,000 species have so far been described (Groombridge, 1993), but there is no doubt that the mites as a group have been neglected because they are harder to find and less immediately appealing than insects. If we assume that the differences in species composition between one place and another, and one habitat to another, are much the same as for insects then this would mean at least several hundred thousand species of mites in the world—nearly all of them so far undiscovered. It is not clear whether mites really should be assumed to follow similar patterns in diversity to insects, for they have their own biology and habits, but this is at least a reasonable basis for a first guess. Another study that indirectly tried to estimate global diversity of mites was Erwin's (1982) study which lumped the mites in with insects, as fellow arthropods.

6.9 ESTIMATING THE UNKNOWN SPECIES RICHNESS OF TROPICAL INSECTS

From what we know of biological diversity to date, the majority of species in the world are insects, and most of them live in the tropics. Tropical forests cover only 7% of the Earth's surface, but they may contain more species than all the rest of the world combined. Recent studies of forest canopies in different parts of the world suggest that tropical forests contain roughly ten times the species richness of insects and other arthropods (such as mites, pillbugs, and millipedes) per unit area, compared with temperate forest. However, within tropical forests there is a lot of local-scale variation in the composition of insect faunas that varies with the conditions in the canopy, such as the abundance of epiphytes (plants growing up on the branches of big trees). It is also uncertain just how widespread each insect species is on average: if you have the same species occurring over large areas this makes for a lot fewer species than if most species have very localized distributions and are replaced by other species in other localities. This patchiness in insect faunas in rainforest canopies makes for a lot of difficulty in figuring out just how many insect species there are. Discussions of the species richness of tropical canopies are in fact central to the whole question of how many species there are in the world. Some estimates put the number of species of arthropods in tropical forest canopies as high as 30 million to 100 million species (most of them still undiscovered).

How were these estimates of total insect diversity arrived at? They depend mostly upon limited local-scale studies where insects in the canopy are killed by spraying insecticide from a machine hoisted high up into the trees. The insects are then collected on sheets or nets as they drop down to the ground. A classic early study using this technique, known as "fogging", was carried out by Erwin (1982) in Panama. He took 19 trees all of one species (*Luehea seemannii*), scattered through a rainforest reserve. Over three seasons, he saturated the canopy of each of his selected trees with a fog of insecticide, and collected the insects that dropped out. He decided to concentrate just on the beetles, and the sample included 1,100 species

of beetles! Many of these were already known species, but many were new to science. The important thing here, though, is only how many species there were in total—either new or previously known.

The next key step was to take a guess at how many of those beetles were unique to the type of tree that they were found on. With a certain sleight of hand, Erwin then estimated that 160 of his sample of beetle species were host tree–specific (i.e., found only on that one species of tree).

So now Erwin had a figure for the beetles on that type of tree in the rainforest, but there are a lot more creepy-crawlies up there in each tree than beetles alone. Beetles represent about 40% of all known arthropod species (the group including insects, mites, etc.), therefore Erwin estimated $160 \times 100/40 = 400$ arthropod species that live only on each tree species.

But, another thing that has to be considered is that not all of these creepy-crawlies live up in the canopy. Some spend most of their time on the ground, on the forest floor. Erwin estimated that the rainforest canopy is roughly twice as species-rich as the forest floor, and that the species there are quite a different set from those up in the canopy. Therefore, including the forest floor this brings the total to 600 arthropod species per tree species.

Erwin then multiplied this figure by what he considered to be the likely total number of *tree* species in the tropics—each presumably with its coterie of narrowly adapted insect species. The estimated total number of species of tropical trees in the world is around 50,000. Therefore, the total number of tropical arthropod species is estimated as $600 \times 50{,}000 = 30$ million. So the figure he arrived at was a stunning 30 million arthropod species—far in excess of the million or so species so far discovered.

Elegant though it is, each step of Erwin's argument has a fair amount of uncertainty surrounding it. For example, if the fraction of arthropod species specific to that tree species were only half the number he had estimated, then the total estimate of species in the world would be reduced by half. Another thing is that the species on the forest floor might not be particularly specific to that one type of host tree, for example. After all, these are mostly just feeding off the junk that falls off trees all around: dead leaves, and fruits all mixed in together, plus the dead bodies and waste material of other creatures that feed off these on the trees; so it is hard to believe that they would be that choosy about exactly which tree they live under. Another thing that adds to the uncertainty is that the diversity of arthropods in the canopy might have either more than or fewer than 40% beetle species. Furthermore, for all we know, the one type of tree Erwin examined might not be typical of tropical rainforest trees in general.

What many ecologists regard as a more reliable estimate of the total number of species of insects in the world comes from a study on tropical rainforest bugs (the group known as hemipterans) on the island of Sulawesi in Indonesia by Hodkinson and Casson (1991). They sampled hemipteran bugs over a one-year period using several sampling methods at several sites including a variety of host trees—not just fogging with insecticide but also using various sorts of traps set to catch the insects.

Hodkinson and Casson's study was based on how easy it was to find new species never before described by science, so it is along similar lines to the studies I referred to above for the deep sea. They found that the rate of accumulation of previously unrecorded hemipteran species leveled off towards the end of the study period, indicating that they had by now identified a substantial proportion of the species in that area. They found a total of 1,690 hemipteran species of which only 37.5% were previously known to science. Globally, at that time the total number of described species of hemipterans was 78,656. Therefore, a simple estimate for the real global total of hemipteran species (including those not yet discovered) is:

$$\begin{pmatrix}\text{total known hemipterans}\\ \text{in world}\end{pmatrix} \times \begin{pmatrix}\text{percentage of new species findable}\\ \text{in an area thoroughly searched}\end{pmatrix} = \begin{pmatrix}\text{total estimated hemipterans}\\ \text{both known and unknown in the world}\end{pmatrix}.$$

So this calculation goes:

$$78{,}656 \times 100/37.5 \;=\; 209{,}000.$$

Hodkinson and Casson suggested hemipterans represent about 10% of all described insect species; therefore, the estimate for the total number of hemipteran species is about 2.1 million, giving an estimate for the total species number for insects of about 5 million—consistent with earlier intuitive estimates from taxonomists. However, unlike Erwin's study this is not a figure for all arthropods, and if it were applied to all the rainforest arthropods it would presumably add a few million more.

Always with such local-scale studies of insects in the rainforests, the global total one comes up with for species richness is highly sensitive to assumptions. In Erwin's (1982) study, a key assumption (and potential weakness) is how host-specific insects tend to be to particular species of trees. Some recent studies by Novotny *et al.* (2002, 2006) in New Guinea suggest that tropical forest insects are not nearly as host-specific as Erwin or most other tropical biologists had assumed. Another fairly major uncertainty is what proportion of each group (e.g., beetles, or hemipteran bugs) represents all the insects or arthropods in the world. Hemipteran bugs in particular happen to have been a popular group for taxonomists to work on—being as they are relatively large and often colorful insects. This means that they are probably over-represented in the species lists, and that in turn means that there are really more non-Hemipteran insects than we might think, and thus more insect species in the world than Hodkinson and Casson estimated. Groombridge and his colleagues (1992) estimated that hemipterans may really only be around 5% of all the insect species in the world—and that would put the total global estimate of insect species up to around 6.5 million to 11 million species!

Another important aspect to consider, if one is sampling only canopy insects, is the proportion of insect or arthropod species that live instead on the forest floor and in the understory layer of shrubs and small trees. For example, some studies (data from Hammond's 1990 study in Sulawesi, Indonesia, see below) suggests that there are actually a lot more species of arthropods (maybe twice as many) in the lower parts of the rainforest below the canopy, and this would be typical also of what is found in

temperate forests. Having proportionally more species in the lower parts of the rainforest would tend to multiply up the number of species in the world beyond those only in the canopy. But then again we don't know if these species living near the ground are really host-specific or can just occur under any type of tree: if they are not selective about where they live and there are just the same species throughout the forest, this would lower the estimate.

In yet another attempt at trying to estimate global insect species richness, Hammond (1990) tried a third type of number-juggling trick. Based on looking at the beetle (coleopteran) species richness of sites in the tropics in Sulawesi (the same Southeast Asian island coincidentally where Hodkinson and Casson worked, see above), he noted that there seem to be typically about five times as many beetles as one would find at a site in the temperate zone. Now we have 0.2 million species of beetles described from colder regions outside the tropics. Probably a fairly high proportion of all the world's temperate beetles have already been found, given how much work has been done on them by the relatively abundant entomologists of those parts of the world. Hammond suggested that about half the outside-the-tropics (extratropical) species of beetles have been found and named by now, judging by how often new species are found. That gives 0.4 million species of extratropical beetles. If we assume that the ratio found at select sites such as Sulawesi holds true generally for the tropics, this means we have to multiply the 0.4 million species of extratropical beetles by 5 to get the number in the tropics—that brings up the global beetle total to 2.4 million species. Assuming that about a third of all insect species in the world are beetles, we then have to multiply our total of 2.4 million by three to get the true global species richness total—and this gives an estimate of 7.2 million insect species.

Another twist on using Hammond's results comes from using his raw collecting results in a different way. This relies on scaling up from the numbers of beetle species he found in his local-scale tropical study to a global total (Groombridge, 1993). In his intensive collecting, Hammond found 6,000 beetle species at his tropical rainforest sites. Assuming he found all the beetle species in that locality, and making further assumptions about how widespread each species was, this could scale up to 1.8 million species globally. If beetles are about a third of all insect species, this translates into somewhere between 5 million and 6 million insect species. However, this all involves a great deal of assumption about how localized each species is on average. For example, if most of the species that Hammond found are really a lot more widespread than he thought, the total estimate would have to be lower.

There have been several other published studies in the last 15 years or so, and though they use slightly different methods and assumptions they all seem to arrive at a figure of between about 5 million and 10 million arthropod species in the world. For example, Odegard (2000) had a go at sifting through the data that others had gathered, and challenged some of the previous assumptions (e.g., about the proportion of species that live in rainforest canopies and how narrow a range of tree species each insect will be found on). He reached what is nowadays the fairly typical conclusion, that the true figure is around 5 million to 10 million species of arthropods, the majority of them insects.

6.10 SO, HOW MANY TYPES OF ARTHROPODS ARE THERE?

Despite the huge amount of effort that has gone into describing insect species by taxonomists, and the fascination that biologists have with estimating how many more remain undescribed, it is frustrating to have to admit that we still do not have a firm idea of how many insect and arthropod species there are in the world. Looking at the estimates arrived at by the various approaches outlined above, and averaging out the more recent and better received ones, a reasonable guess would be that the true figure is about 4 million to 7 million insect species, and at least a couple of million more arthropods of other kinds—bringing about a total of around 6 million to 9 million arthropod species.

6.11 CRYPTIC DIVERSITY

It is not always necessary to look in remote rainforests or the deep oceans to find new species. Hidden diversity is right under our noses out in nature, wherever we live. Sometimes, even in densely populated and much-studied parts of the world, taxonomists still find things that clearly, obviously belong to new species and unsurprisingly, most of them are arthropods. This even happens from time to time in my native England, which from a natural history viewpoint is one of the most thoroughly picked-over places on Earth.

But there is another sort of hidden diversity that is all around us: the diversity that exists *within* the lists of species that are already known. Over the last several decades, detailed study has sometimes revealed that what was thought to be a single species is actually several different species, which do not interbreed with one another. These hidden species are known to biologists as "cryptic" species.

Cryptic species have been found within groups as different from one another as tropical butterflies, deep-sea clams, freshwater fish, and Arctic plants. Over the past 50 years, more than 3,500 scientific papers have been published on the subject (Bickford *et al.*, 2007). Looking across the range of cryptic species discovered so far, relatively few of them are higher plants or microbes. The majority of those that have been found are temperate zone organisms, but this can only be because temperate-zone life has been closely studied enough to pick up the cryptic species that exist there. It is likely that the tropics hold many times more cryptic species that have not yet been discovered, simply because the vast diversity of the tropics has never been studied in such detail.

Though the different cryptic species in a group often occur separately in different places, in some cases they have overlapping distributions. So while some of the birds or insects we may see in a place belong to one species, other identical-looking ones in the same trees can sometimes belong to another species.

Sometimes cryptic species were first found just by taking a closer look at external color patterns, anatomy, or some other feature—so that what had been thought to be one species turned out to be two or more quite distinct forms with their own behavior and breeding patterns. One example is the two species of thrushes in the genus

Catharus in North America. The gray-cheeked thrush (*Catharus minimus*) and Bicknell's thrush (*Catharus bicknelli*) used to be classified as one species, which is understandable as they are only distinguishable to human eyes by a slight difference in their average size. It is not always the case, though, that we can actually find a simple identifying feature that is recognizable to the human eye.

Some cryptic species were first discovered by looking at the chromosomes—the packages of DNA in the nucleus—that show up within dividing cells stained under the microscope. In certain of these cases, what had previously been thought of as just a single species of animal or plant turned out to be several different ones: their chromosomes were so different that each type would be unable to interbreed with the others. This is because having mismatched chromosomes can cause a whole range of problems for any hybrid organism that is produced between the species. For example, if their chromosomes do not match up properly at the time of meiosis (when sperm or eggs are produced), the hybrid offspring will be sterile.

Other groups of cryptic species have been found using more modern genetic tools that focus on the details within chromosomes, not their overall shape. This requires DNA-sequencing technology, looking for differences in the genetic codes of different populations within a species. Often after cryptic species have been distinguished from one another using chromosomal shapes or DNA sequence evidence, certain subtle diagnostic features for each of these newly found species are found in terms of their body form (e.g., the number of bristle hairs found on the leg of a fly may mark one cryptic species off from another).

Although DNA studies can be very useful in looking for cryptic species, they should not be used as a substitute for careful classification work. It is quite possible to have two populations of the same species that seem very distinctive in DNA sequence terms, yet quite able to interbreed—presumably because the genes which are different do not affect the function of the organism too drastically, while the ones that remain about the same are the really important ones. So, overall DNA sequence difference in itself is not really the key factor in causing organisms to belong to different species. If we are not careful in checking out the biology and behavior of the creatures we are studying, we could easily end up filling the world with imaginary species.

Some well-authenticated complexes of cryptic species have been found in economically or medically important groups of insects (e.g., mosquitoes; these are important because they carry disease). For example, there is the *Anopheles gambii* complex: several species of mosquitoes which look the same to us but do not interbreed with one another, each species having its own distinct behavior pattern. Some of them are important as carriers of human malaria, while others never bite humans. Clearly, if we want to understand mosquito breeding habits, malaria transmission, and control strategies, it is important to know which particular species we are dealing with!

In organisms that have less practical significance to humans, it is generally too time-consuming and expensive to be worth doing the exploratory work that would be required to find out if there are cryptic species around. It is quite possible that this "hidden species diversity" is far more common in nature than we realize. Humans tend to classify the world in visual terms, but for many other groups of organisms this

is not the case, and they use non-visual clues such as sound or odor to distinguish themselves from other related species. Thus it is thought that cryptic species (cryptic from our point of view, anyway) are more common in groups that rely heavily on these other cues for choosing their mates. For example, relatively drab birds such as the North American thrushes (*Catharus*) and Old World warblers (family Sylviidae) use details of song to distinguish which of their neighbors belong to their own species. Mosquitoes use the detailed pitch of sound generated by the wings, while many other insects use a precise combination of volatile chemicals (pheromones) produced by the male, the female, or both. Frogs also tend to rely on both calls and pheromones. These are all traits that tend to go unnoticed by humans, likely leading to the existence of undiscovered cryptic species. It can be quite a revelation when every once in a while we discover how much we were missing: a group known as the rhacophorine frogs in Sri Lanka suddenly expanded to more than a hundred species after many of the original 18 named species turned out to consist of groups of cryptic species.

There are also many life forms that do not have much morphological complexity that we could ever use to distinguish them by eye. For example, sponges have a very simple form, so their species are often by nature cryptic.

Another factor tending to lead to cryptic species (that look similar or identical to our eyes) being produced is a certain niche that is very demanding in terms of the exact physical form of the organism. For example, Antarctic bonefish living in an extreme environment of very cold water under floating ice are one example of a group that has produced many species, with little change in physical form.

It used to be thought that all groups or pairs of cryptic species had only recently diverged from one another, perhaps in the last few tens of thousands of years. In fact, DNA studies show that very often they have been separate for millions of years. For example, the cryptic species of bonefishes, plus many cryptic species of amphipod and copepod crustaceans, turn out to have diverged millions of years ago.

6.12 FALSE SPECIES DIVERSITY: SPECIES COMPLEXES

In some other cases, what we find is really the opposite problem: "false species diversity". Sometimes what seemed to be several separate species, each one having quite a distinctive look about it, turn out only to be different populations of a single species. They may all be capable of interbreeding, and if we were to study these populations closely enough they might also be found to intergrade in nature. Interbreeding and intergradation breaks the formal definition of a species in biology, which is essentially "something that it is distinct in form and does not interbreed with anything else". These clusters of false species are known as "species complexes". In the plant world they sometimes also go by the name of "ochlospecies", the Greek word *ochlo* meaning a crowd.

An example of a species complex that is just now being uncovered is the "scarlet oak" complex of eastern North America. Scarlet oak (*Quercus coccinea*) is one of the commonest trees in the eastern forests, and for more than two centuries botanists

have thought of them as separate and distinct species. Yet now they are finding a plethora of clues suggesting that this "species"' actually intergrades with several other eastern U.S. oak species (such as willow oak and southern red oak), to form one big "super-species". The evidence comes partly in terms of careful examination of the form of leaves, flowers, and fruits of the trees, which shows that many individuals have mixed combinations of traits that do not seem to fall into any one species. This is confirmed with studies of DNA from the chloroplasts—photosynthetic bodies in the plant cells—which show that indeed the different "species" are often exchanging genes. The chloroplast DNA of the other oak species in one locality is often the same as that of the scarlet oaks nearby (Jeanne Romero, pers. commun., 2008).

A famous species complex in the animal world is the "ring species" of gulls of the genus *Larus*, which links populations around the Arctic spanning Scandinavea, Siberia, Canada, and Alaska. Several "species" of gulls across this broad span have been found to merge into their neighbors. All except, that is, the two species where the ends of the ring join, which are in some way too distinct to interbreed. There is a similar ring species in the warblers of the genus *Phylloscopus* whose range loops round the Himalayan Mountains in Asia. To the north of the Himalayas, the various "species" merge. Yet the two forms that hook round to the south from either side do not interbreed where they meet there, even though that are really part of the same complex of species that is busy exchanging genes elsewhere.

In the sea, clamshells (bivalves) seem to show a lot of geographical variation within particular species. In the past, taxonomists often classified these variants as separate species in their own right. DNA studies are showing that in fact many "species" are just different populations that have grown to look somewhat different by being isolated from one another (Bickford *et al.*, 2007).

Where else might species complexes be found? I remember one of my professors from undergraduate days, Frank White, speculating that the tropical rainforests might be full of them. He suggested that many of the tens of thousands of tree species in the tropics are actually just a part of complex species (or "ochlospecies" as he called them), that might vary geographically or perhaps even on a local scale—looking like different species when in fact they are one. This complexity could be fooling us into thinking that there are many more species than is actually the case. So far I have heard no evidence that rainforest trees tend to form ochlospecies. But few tropical species have been really intensively studied—so if they were in fact ochlospecies, would we really know?

6.13 THE HIDDEN WORLD OF MICROBIAL DIVERSITY

Bacteria, viruses, protozoa, and the smaller fungi are abundant everywhere, but they represent the greatest challenge in terms of species richness. Microbes have always been difficult to classify in terms of species, because they have such a simple physical form. One species of bacterium, protozoan, or fungus tends to look a lot like many others under the microscope, and since taxonomy has traditionally been

based on morphology, there was not much basis to distinguish them on. Could there be a vast hidden world of species richness in the microbial world, unseen and all around us? The existence of enormous hidden microbial diversity is now becoming apparent, with the aid of new molecular techniques. So far the work has mainly focused on bacteria, but other groups will no doubt soon become subject to similar scrutiny.

It is becoming increasingly obvious that the traditional ways of counting up numbers of bacterial species in samples from nature (taken from soil, water, or whatever) miss most of the diversity that is really out there. For more than 150 years, bacteria have traditionally been identified by culturing them out from very diluted samples, spread onto a Petri dish or floating in a bottle of a growth medium—essentially a soup full of nutrients. Each colony that forms in culture is identified under a microscope or using special techniques for staining and biochemical activity. For this to be a reliable way of finding what species were present in the initial sample, one requirement would be that most species actually grow in a culture medium. It now seems that all along, this was not the case: most species were being completely missed. A new set of techniques based on picking out the DNA sequences present in raw samples from nature shows that many, many forms that are present in samples simply do not grow in culture. Hence they had always been missed, and gone uncounted. As an example of how much more can be found, Gans *et al*. 2005 found around a million quite distinct forms of genes coding for ribosomal RNA sequences in a few grams of soil. Within each of those bacterial "species" that have been studied in detail and seem to correspond to what we would normally call a species, the gene for the rRNA, as it is called, does not tend to vary—so this implies that each of these gene types in the samples comes from a separate species. In the bacterial world, the equivalent of the plant and animal diversity we might find in a whole region of tropical rainforest is concentrated into a single pinch of soil!

The initial studies set off a scramble to catalog the bacterial diversity of different environments on Earth. Now everywhere they look using these molecular techniques, microbiologists are finding similar levels of diversity: what look like millions of bacterial species, many of them not previously found in the other environments that have been sampled.

Complicating the business of cataloging species richness of bacteria has been the discovery that many different types of bacteria are able to exchange genes directly with others that would not normally be regarded as belonging to the same species—because these have such a distinct biochemical makeup, or most of their DNA is quite different from one another. In this sense, the traditional definition of "a species"—unable to exchange genetic information with others—breaks down for bacteria living out in nature. Perhaps much of the total diversity of bacterial life could better be described as one huge species complex (see above) through which any gene can gradually spread if it carries some advantage for its host.

The problems with identifying species of bacteria are also found to some extent with fungi. Although their cell structure and the form of their fruiting bodies is a lot more complex and variable than in the case of bacteria, they are still hard to discern from one another. Once again, growing things in cultures has been the

traditional way of finding and identifying species of fungi—yet we cannot be sure how many types there are in each soil sample that have simply failed to grow. Molecular techniques may eventually show us how many species have so far gone unnoticed.

6.14 NATURE STILL YIELDS SURPRISES

Most new species of animals and plants are fairly similar to forms that have already been found, usually in the same genus as previously named and described species. But every once in a while, a new species is found which stuns those who discover it: something novel enough to be featured in news media around the world. Most dramatic of all are life forms that are in a sense both old and new: "living fossils". Living fossils are life forms that were known from the fossil record but thought to be long extinct. It is as if someone had gone back in a time machine and brought us a real live specimen. In just the last few years, two such living fossils have been found, one of them a plant, the other an animal.

In 1997, a ranger at the Wollemi National Park in Australia abseiled down a steep gulley and found a strange-looking tree. It turned out to belong to a genus of conifer that was last known from 30 million years ago, related to the monkey puzzle tree (*Araucaria*) of Chile and the kauris (*Agathis*) of Australia and New Zealand. The Wollemi pine (*Wollemia*), as it is called, had somehow survived in three tiny populations totaling just a hundred or so individuals, barely clinging to existence in gullies close by one another. Almost as amazing was the fact that its refuge was only 50 km from Sydney, the largest city in Australia with several million people.

In 2002, zoologists on fieldwork in Laos found a strange animal on sale in a village market. It was a rat-squirrel (*Laonastes aenigmamus*), something akin to the common ancestors of the rats and mice on one hand, and squirrels on the other. Forms very much like it had existed 20 million years ago, known from fossils, and yet here it was alive in the present-day world.

Sometimes, species thought to have gone extinct in the much more recent past have been rediscovered, alive and well. For example, the Bermuda petrel (*Pterodroma cahow*) was thought to have gone extinct around 1615, but to the amazement of ornithologists 18 pairs were found alive in 1951. The population has now expanded under protection to about 150 individuals.

Discoveries such as these remind us that we do not know everything that is out there, and that in addition to finding more nematodes or more beetles, there may still be some genuine surprises out there awaiting us.

6.15 THE SHADOWY WORLD OF CRYPTOZOOLOGY

While we can be sure that there are many species out in nature that have not yet been discovered, there are some that seem to exist in a twilight zone of the human imagination—suspected by at least some serious biologists, but never having been formerly captured and described, and dismissed as myths and wishful thinking by

many others. The business of investigating claimed but unproven animals is known as "cryptozoology". In some senses crypozoology has a venerable history: many unusual life forms were first known from scattered, fleeting sightings or tribal legends, and treated with skepticism or even derision by scientists at the time. The gorilla (*Gorilla gorilla*), for example, was regarded as a mythical animal until a skull was obtained in 1847. It is the same story with the giraffe-like Okapi (*Okapia johnstoni*), discovered in 1901. However, cryptozoology also tends to attract amateurs and eccentrics, whose zealous enthusiasm has helped ensure that cryptozoology is banished to the sidelines of respectable science.

Often, the animals that are purported to exist by cryptozoologists are "living fossils", resembling species that are known from the fossil record but which are generally agreed to have died out. Among the more widely accepted of these "living fossils" is the yeti of Nepal and Tibet, said to be a large upright-walking ape covered in shaggy reddish hair. It is purported to be a living descendant of a rather similar fossil form *Gigantopithecus*, which survived in western China up until half a million years ago. With a background of many centuries of reported sightings continuing up to the present, the yeti is an integral part of folk culture in the region. Intriguingly, mysterious ape-like footprints have been found in snows high up in the Himalayas, including a set of tracks examined in detail and photographed by a British expedition in the 1920s. It is difficult to explain these away as being simply a hoax or the tracks of some other animal. On the other hand, there is the puzzling lack of any recent physical remains or droppings of these creatures, although in the first half of the 20th century expeditions did claim to find these. In those days, DNA analysis was not available but hair, skin, and feces could be compared with those of other known creatures. Those who gathered and analyzed the samples tended to note that the samples (and the parasites within them) did not resemble known forms that lived off other animals in the region—and then always the samples were lost—conveniently, some might say. Recent news reports (BBC, January 2009) mentioned another "yeti" hair sample, which was analyzed for its DNA. It turned out to belong to a species of wild goat.

Occasionally, respected naturalists have made fools of themselves by declaring too early the existence of something which did not turn out to be supported by the evidence. The most famous example was when Sir Peter Scott declared the existence of the legendary "Loch Ness Monster", on the basis of a sonar photo of a diamond-shaped fin in the loch, which resembled the fins of the plesiosaurs of the Mesozoic period. The photo turned out to have been greatly retouched from the original, which offered only a very vague pattern, and it is now generally regarded as a hoax. Scott had even coined a Latin name for the monster: *Nessiteras rhombopteryx*. Adding to the embarrassment, someone pointed out that this was an anagram of "Monster hoax by Sir Peter S".

Other well-known tales in cryptozoology involve species that are generally thought to have gone extinct in the recent historical past, but may have been sighted since. The most famous of these in recent years has been the ivory-billed woodpecker (*Campephilus principalis*) (Figure 6.3). This very large woodpecker—with a wing span of about 75 cm—was formerly widespread through the southeastern United States,

Figure 6.3. The ivory-billed woodpecker. Extinct in the 1940s—or is it? (source: Audubon). *See also* Color section.

where it nested in holes in large old swamp cypress (*Taxodium*) and pine (*Pinus*) trees. The ivory-billed was reportedly nicknamed the Lord God bird, because people seeing it for the first time would often exclaim "Lord God, what's that?!" Felling of the old growth cypress and pine forests across the South occurred on a large scale between the 1860s and 1920s, and eliminated the ivory-billed from most of its range. The last confirmed specimens were seen in the early 1940s in a tract of cypress swamp in Louisiana which was subsequently cleared. There had been sporadic reports of sightings through the last several decades, but these were generally met with skepticism. Then in 2005, Fitzpatrick *et al.* (2005) announced the probable rediscovery of the ivory-billed, based on sightings and a video of the bird taken in a

surviving old-growth cypress swamp in Arkansas. This was at first met with a wave of euphoria, later dampened when another group of ornithologists claimed that the bird seen in the video was more likely a common pileated woodpecker, not an ivory-billed. Listening devices stationed in the forest later seemed to pick up the distinctive "double rap" of ivory-bills, and the scientists who had claimed the video did not show an ivory-billed woodpecker now accepted the audio evidence of the bird existing there. However, there are a number of prominent skeptics remaining who suggest that the double raps have other sources, and there have been no apparent sightings of ivory-bills in the area subsequently. So at the time of writing, the ivory-billed remains basically in limbo—neither fully extinct nor fully alive in the collective consciousness of science.

Another possible example of a "crypto-species" is the thylacine or Tasmanian wolf (*Thylacinus cynocephalus*). This marsupial carnivore was very similar to a dog, representing a striking example of the process known as convergent evolution that molds species from diverse origins into the same niche. The most obvious difference from dogs, however, was a set of stripes along its back, which may have served as camouflage in hunting. Thylacines were once widespread all across Australia and the island of New Guinea, but they died out several thousand years ago—presumably as a result of competition with the dingo, an introduced placental dog from Asia (Chapter 5). By the time Europeans arrived, the thylacine only survived on the island of Tasmania, where the dingo had never been introduced. Deforestation, persecution by farmers, and perhaps competition with introduced dogs and cats ensured that the last known thylacine was dead by 1936. However, there have been many reports of sightings of a thylacine-like animal. These reports were taken seriously enough to warrant the setting up of a thylacine "reserve" in Tasmania, perhaps the world's only reserve designated for an animal which might or might not exist. Reported sightings of the thylacine were not only on Tasmania but also on the Australian mainland, and apparently also from aboriginal people from northwestern Iryan Jaya. Several times, photographic or video evidence has been purported to show the thylacine, but the quality to the images is always poor. The common concerns of zoologists are that they might represent another known species of animal (such as a wallaby), or that they may be outright fakes. Skeptics reasonably ask why—if the animal still exists—no tracks or droppings have been found. Once again, the thylacine exists only in the twilight, with the quality of evidence for its survival being poorer than that for the ivory-billed woodpecker.

6.16 THE TWILIGHT WORLD OF SPECIES RICHNESS

It is not just the thylacine, the yeti, and other semi-mythical forms that exist in the twilight. Much of the diversity of nature, indeed most of it, is unseen and unknown. Almost certainly, the majority of species in the world have not yet been discovered. Science has never seen them, but it feels it knows that they are there. Most of these undiscovered species will be fairly mundane: worms or beetles or rainforest trees that belong to groups that are already well known. Yet these unknown life forms may yet

include some weird and wonderful things, perhaps ones thought to have gone extinct long ago. However, we should be wary of the wishful thinking that often drives a belief in such things among enthusiasts and the general public.

In a sense then, most of the present-day world's diversity exists in an unknown state: it exists yet does not fully exist. The situation reminds me of quantum uncertainty in physics—an intermediate state that might only exist in the mind of the observer. It is rather unsettling to have to admit it, but most of the species richness that this book deals with is still more or less imaginary.